

ELECTRONIC FUNDAMENTALS

THEORY LESSON 16

A-C CIRCUITS

- 16-1. Series A-C Circuits
- 16-2. Series Resonance
- 16-3. Parallel A-C Circuits
- 16-4. Parallel Resonance
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Theory Lesson 16

INTRODUCTION

Of the mysteries of the electronics industry, one that puzzles many people is how a radio or television receiver can be tuned to select one particular station and to reject all others. This lesson is mostly about *resonant circuits*; circuits that permit us to select stations and do other useful things.

A-c circuits is one of the most important and difficult subjects in this course. However, when you can say that you understand what happens in resonant circuits, when you learn how selection is made, and when you can answer correctly the questions in the test that appears at the end of this lesson booklet, you'll be ready for any lesson that is still to come. Mind you, we say that this lesson is difficult only because some of the lessons that you have already passed were easier. Having passed the other lessons, you are prepared for this one. All that remains for you to do is to take your time, apply the knowledge you already have, and to be sure that you understand each part before you pass on to the next part of the lesson.

As we have said, this lesson will be mostly about resonant circuits. There are two kinds of resonant circuits: the *series-*

resonant circuit in which an inductor, a capacitor, and an a-c voltage source are connected in series; and the *parallel-resonant* circuit in which a capacitor, an inductor, and an a-c voltage source are connected in parallel. Each circuit has its own peculiar characteristics and effects, which you will want to know about. However, before we discuss resonant circuits, we will start with some simpler circuits, review what you know about them from earlier lessons, add some new facts about a-c resistance, skin effect, coil and circuit Q , and a-c power. Then you'll use this knowledge to help you study series and parallel resonance.

This lesson discusses things that you should know about a-c circuits. Formulas and calculations are kept to a minimum and are given only when they are necessary to help you understand the theory. The lesson assignment that appears at the end of this lesson covers this material only. The Appendix shows typical a-c circuit problems worked out step by step. If you want to see how series- and parallel-resonant circuit calculations are made, or if you wish to work some out for yourself, turn to the Appendix. Answers to the practice problems are given so that you may know if your calculations are correct. *However, these practice problems are not part of the lesson assignment, so do not include the answers when you mail your completed assignment.*

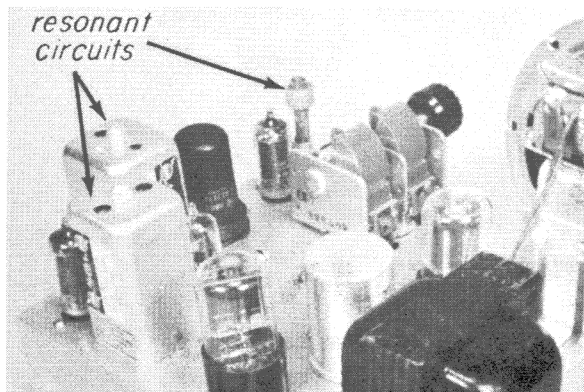


Fig. 16-1

16-1. SERIES A-C CIRCUITS

Let's review a few things that you learned in earlier lessons. First, look at Fig. 16-2a. It shows a simple circuit with a resistor R , an inductor L , and an a-c voltage source E connected in series. You learned in your study of inductance that the resistive volt-

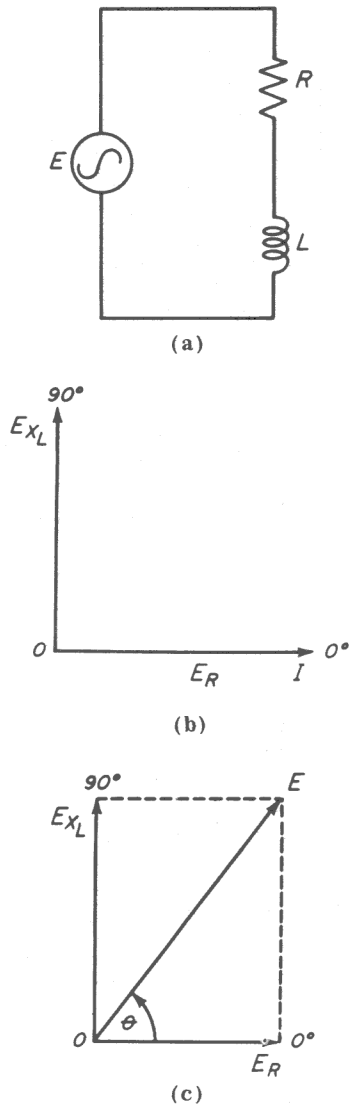


Fig. 16-2

age is in phase with the line current, while the reactive voltage leads both resistive voltage and line current by 90 degrees. We can show these conditions with a vector drawing (Fig. 16-2b). You know, too, that the line voltage E is equal to the vector addition of E_R and E_{X_L} , as in Fig. 16-2c. You know that the impedance of the circuit may be found by using the formula:

$$Z = \sqrt{R^2 + X_L^2}$$

And you know the cosine of angle θ is equal to R divided by Z , which may be used to find the phase angle. We won't assign any values to R , L and E at this time. If you want to brush up on any of the material in this paragraph or in the following paragraph, review Theory Lessons 14 and 15.

Look at Fig. 16-3a. It shows a simple a-c

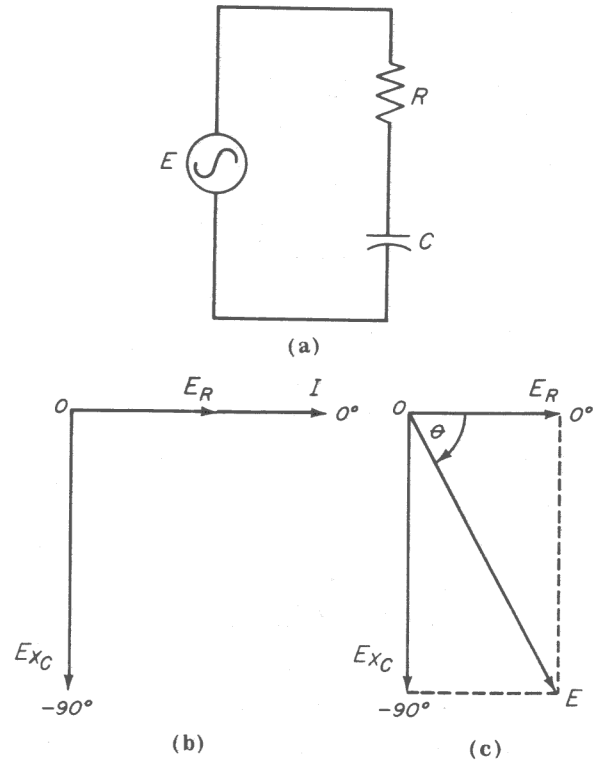


Fig. 16-3

circuit with a resistor R , a capacitor C , and a voltage source E connected in series. In Theory Lesson 15, you learned that the resistive voltage of such a circuit is in phase with the current and that the reactive voltage lags both resistive voltage and line current by 90 degrees, as shown by the vector drawing (Fig. 16-3b). You learned that the line voltage E is equal to the vector addition of E_R and E_{X_C} , as in Fig. 16-3c. You know that the impedance of the circuit may be found by using the formula:

$$Z = \sqrt{R^2 + X_C^2}$$

And you know that the cosine θ is found equal to R divided by Z .

Now let us look at something different. Figure 16-4a shows an inductor L and a capacitor C connected in series with an a-c power source E . We will assume that L has only pure inductance and that C has only pure capacitance. This being the case, the phase difference between the reactive voltages is 180 degrees. When X_L is greater than X_C , the reactive voltages may be represented by the vector drawing, Fig. 16-4b. Because an inductive-reactive voltage is directly opposite in polarity to a capacitive-reactive voltage in the same circuit, one can-

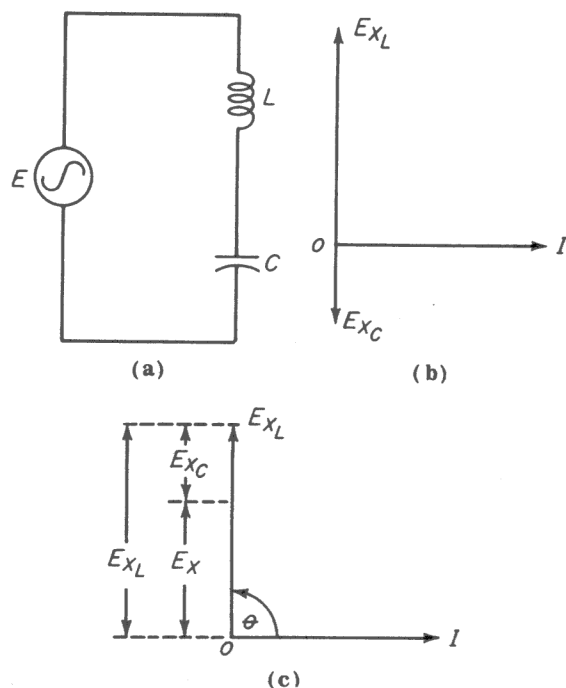


Fig. 16-4

cels the other. Therefore, the net reactive voltage may be found by subtracting the smaller voltage from the larger. So we mark off the length of the E_{XC} vector from the end of the E_{XL} vector, as shown in Fig. 16-4c, and what is left represents the total reactive voltage of the circuit. Because we are assuming that there is no resistance in the circuit, the total reactive voltage is equal to the line voltage E , which leads the current by 90 degrees. Because the voltage is leading, the circuit is inductive. However, when the capacitive voltage is larger than the inductive voltage, as in Fig. 16-5a, the smaller E_{XL} is subtracted from the larger E_{XC} (Fig. 16-5 b) and the remainder represents the total reactive voltage of the circuit. As there is no resistance, this voltage is equal to the line voltage E , and lags the current by 90 degrees.

In the series circuit (Fig. 16-6a) the resistance of the circuit, which is due to the inductor, is represented by a resistor symbol marked R_{coil} . The in-phase voltage due to this resistance is drawn as E_R and the inductive voltage as E_{XL} in the vector diagram (Fig. 16-6b). The resultant of these two voltages, E_{coil} , is the voltage that we actually measure across the coil. While the reactive voltages are 180 degrees out of phase, the voltage we actually measure across the coil — E_{coil} — is less than 180

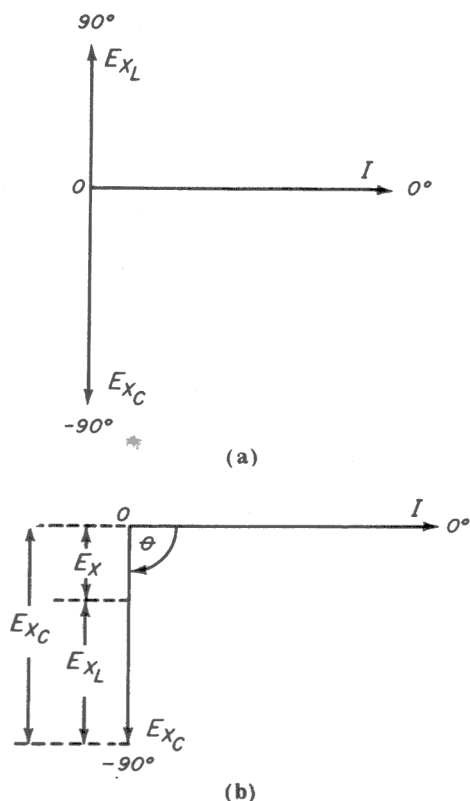


Fig. 16-5

degrees out of phase with the voltage across the capacitor, E_{XC} . Where coil resistance is very small, the E_{coil} and E_{XC} may be *almost* but never *exactly* 180 degrees out of phase.

When the inductive voltage is greater than the capacitive voltage, the voltage vector for the circuit looks like that in Fig. 16-6c. When the capacitive voltage is greater than the inductive voltage, the vector drawing looks like that in Fig. 16-6d. In both cases, because there is resistance in the circuit, the resultant reactive voltage, E_X is not the same as the line voltage E . Note that E_{XL} in one case, and E_{XC} in the other case, is greater than the applied voltage E . In such a circuit, it is possible for either reactive voltage, or *both* reactive voltages, to be greater — sometimes much greater — than the applied voltage. Because of this, it is wise to be careful when working around reactive voltage and avoid being burned.

The impedance, Z , of either circuit is found by using this formula:

$$Z = \sqrt{R^2 + X^2}$$

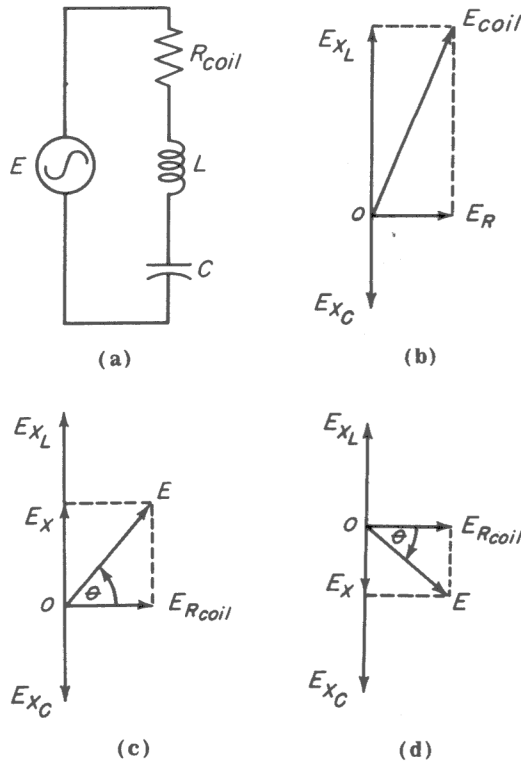


Fig. 16-6

The reactance X is found by subtracting X_C from X_L :

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

If the expression $(X_L - X_C)$ becomes negative (that is, $-X$), the negative sign will disappear when the expression is squared. Let's apply this formula to the circuit shown in Fig. 16-7. Then:

$$\begin{aligned} Z &= \sqrt{R^2 + (X_L - X_C)^2} \\ &= \sqrt{30^2 + (150 - 110)^2} \\ &= \sqrt{900 + 1,600} \\ &= \sqrt{2,500} \\ &= 50 \text{ ohms} \end{aligned}$$

We draw an impedance vector in the same way in which we draw a voltage vector. Inductive reactance is shown leading resistance by 90 degrees and capacitive reactance is shown lagging resistance by 90 degrees. Figure 16-8a shows the vectors of the resistance and reactances of the circuit in Fig. 16-7. In Fig. 16-8b, X_C has been measured off on the X_L vector, leaving X ,

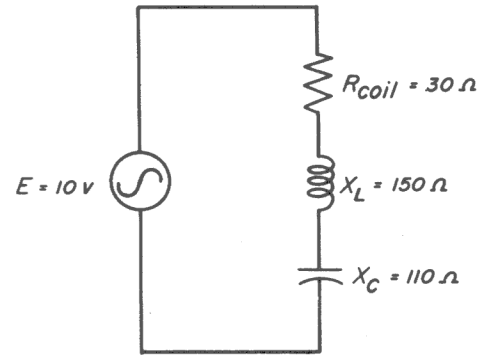


Fig. 16-7

which, with R , permits us to draw Z . The circuit is inductive, and the phase angle of lagging current may be found by;

$$\begin{aligned} \cosine \theta &= \frac{R}{Z} \\ &= \frac{30}{50} \\ &= 0.60 \end{aligned}$$

Referring to the cosine table in Lesson 15, we find that the phase angle is approximately 53 degrees.

Power in A-C Circuits. The power in a d-c circuit may be found by multiplying the voltage by the current ($E \times I$). This may be done in a-c circuits only when the circuit is purely resistive. The product of E and I in any circuit containing reactance cannot possibly give the actual power because the

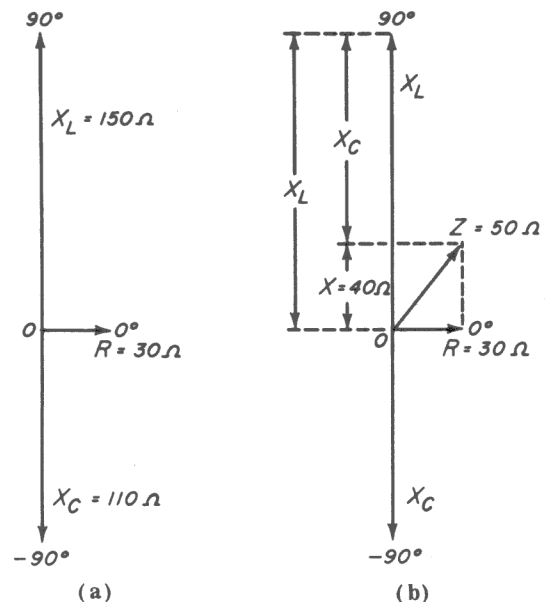


Fig. 16-8

current and voltage are out of phase. Instead, in a reactive circuit, E multiplied by I gives a quantity known as the *apparent power*, which is measured in volt-amperes (abbreviated VA) instead of watts. In a reactive circuit, the *true power* is always less than the apparent power. The true power is equal to the apparent power times the *power factor*.

The power factor is equal to $\frac{R}{Z}$ or or cosine θ . When the circuit is resistive, when $Z = R$, the power factor is 1. The power factor (abbreviated pf) varies between 0 and 1. It is used in this way. Suppose that the voltage applied to a circuit containing reactance equals 100 volts and the current is 2 amperes. The apparent power is then 200 VA . If the resistance of the circuit is 5 ohms and the impedance is 50 ohms, the power factor is found by using the formula:

$$\begin{aligned} \text{pf} &= \frac{R}{Z} \\ &= \frac{5}{50} \\ &= 0.1 \end{aligned}$$

We then find the true power:

true power = apparent power x power factor

$$\begin{aligned} &= 200 \times 0.1 & P_t &= P_a P_f \\ &= 20 \text{ watts} & \frac{P_t}{P_a} & \end{aligned}$$

However, one formula that is true for power in a-c as well as d-c circuits is:

$$P = I^2 R$$

Applying this formula to the problem above, we find:

$$\begin{aligned} P &= I^2 R \\ &= 2^2 \times 5 \\ &= 4 \times 5 \\ &= 20 \text{ watts} \end{aligned}$$

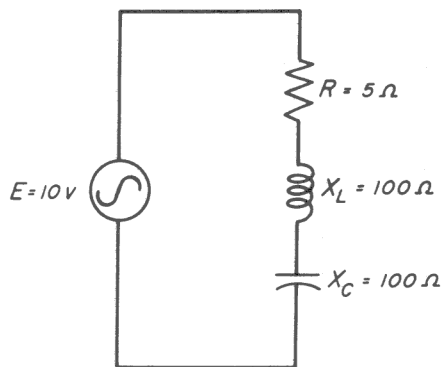


Fig. 16-9

16-2. SERIES RESONANCE

Until now, we have considered circuits where one of the reactances was greater than the other. Let's see what happens when $X_L = X_C$ and the reactive voltages cancel out entirely. Figure 16-9 shows a circuit where R , L and C are in series with the line voltage, and $X_L = X_C$. The impedance of the circuit is:

$$\begin{aligned} Z &= \sqrt{R^2 + (X_L - X_C)^2} \\ &= \sqrt{5^2 + (100 - 100)^2} \\ &= \sqrt{25 + 0} \\ &= 5 \text{ ohms} \end{aligned}$$

From this you can see that when $X_L = X_C$, Z is equal to R . The circuit at that point acts like a resistor of low value, the current and voltage are in phase, and the power factor is 1. This condition in an a-c circuit containing R , L , and C in series is called *series resonance*. For such a case, we say that the circuit is a *series-resonant circuit*.

The straight-line curve of Fig. 16-10 shows how the inductive reactance of an inductor changes with frequency; while the other (rounded) curve shows how the capacitive reactance varies with frequency. At the point where the two curves cross each other, $X_L = X_C$; this point marks the resonant frequency of the series-tuned circuit that contains the values of L and C for which the curves were drawn. At resonance, the impedance is minimum, which means that the current is maximum. At frequencies above and below resonance, the impedance is greater because of the reactance. Look at

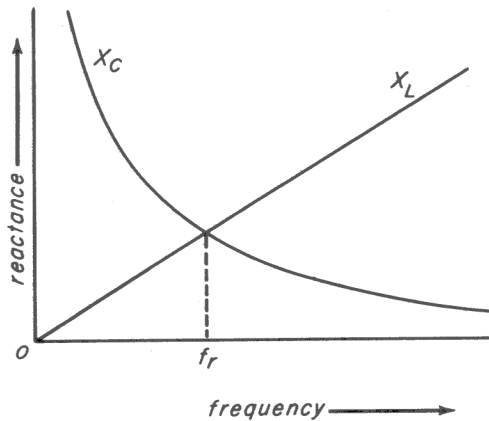


Fig. 16-10

the curves of Fig. 16-10 and you'll see that X_C is greater than X_L for all frequencies below resonance; so, for these frequencies, the circuit is capacitive and the current leads the line voltage. For frequencies above resonance, X_L is greater than X_C , so the circuit is inductive and the current lags the line voltage.

As you know, series resonance occurs when $X_L = X_C$. You know too, that $X_L = 2\pi fL$ and that $X_C = \frac{1}{2\pi fC}$. Therefore, series resonance occurs when $2\pi fL = \frac{1}{2\pi fC}$.

Furthermore:

$$f = \frac{1}{2\pi \sqrt{LC}}$$

In this formula, f is the resonant frequency in cps, L is the inductance in henrys, and C is the capacitance in farads. A more practical formula for finding the resonant frequency in a radio-frequency circuit is:

$$f^2 = \frac{25,300 \times 10^6}{L C}$$

$\begin{matrix} \text{kc} & & \\ \swarrow & & \searrow \\ \text{uh} & & \text{mmf} \end{matrix}$

where:

f^2 = resonant frequency in kilocycles, squared

L = inductance in microhenrys

C = capacitance in micromicrofarads

For example, what is the resonant frequency of a circuit containing a 50- μ h inductor and a 200- μ mf capacitor?

$$\begin{aligned} f^2 &= \frac{25,300 \times 10^6}{LC} = \frac{25,300 \times 10^6}{50 \times 200} \\ &= \frac{25,300 \times 10^6}{10,000} = \frac{25,300 \times 10^6}{10^4} \\ &= 25,300 \times 10^2 = 2,530,000 \\ f &= \sqrt{2,530,000} = 1,590 \text{ kc} \end{aligned}$$

Suppose that we want to find out what value of capacitor is needed to resonate a 100- μ h coil at 1,000 kc. We turn the formula around so that it becomes:

$$\begin{aligned} C &= \frac{25,300 \times 10^6}{f^2 L} \\ &= \frac{25,300 \times 10^6}{1,000^2 \times 100} \\ &= \frac{25,300 \times 10^6}{10^6 \times 100} \\ &= \frac{25,300}{100} \\ &= 253 \mu\text{mf} \end{aligned}$$

Or suppose that we want to find out what value of inductor we need to resonate a 500- μ mf capacitor at 200 kc. We change the formula to read:

$$\begin{aligned} L &= \frac{25,300 \times 10^6}{f^2 C} \\ &= \frac{25,300 \times 10^6}{200^2 \times 500} \\ &= \frac{25,300 \times 10^6}{40,000 \times 500} \\ &= \frac{25,300 \times 10^6}{4 \times 10^4 \times 5 \times 10^2} \\ &= \frac{25,300 \times 10^6}{20 \times 10^6} \\ &= \frac{25,300}{20} \\ &= 1,265 \mu\text{h} \end{aligned}$$

You will notice that nothing is mentioned about resistance in any of these formulas. Yet, in a series-resonant circuit, resistance is a very important factor. If it were not for the resistance of the circuit, the impedance of a series-resonant circuit would be zero at the resonant frequency. In addition, only resistance can absorb power from the source. So, the smaller the resistance contained in a series-resonant circuit, the less is the power lost. The resistance of such a circuit is usually that of the inductor. So inductors are rated for Q , which is sometimes called the *figure of merit* or *quality* of the coil, which is the ratio of the X_L to the R of the coil. (Do not confuse this Q with the quantity-of-charge Q used in Theory Lesson 15.) The formula for Q is written this way:

High Q = Low Resistance
 Q prop. to X_L
 Q inversely prop. to R

$$Q = \frac{X_L}{R}$$

If the inductive reactance of a coil at resonance is 200 ohms and its resistance is 5 ohms, then its Q is 200 divided by 5, or 40. This is not very high because coils with Q 's of 200 or more are often used in radio and television circuits.

The Q of the series-resonant circuit is also X_L divided by R (circuit). However, if there is any resistance in the capacitor or in the circuit connections, the circuit resistance may be higher than the coil resistance. In calculating inductor or circuit Q , R is not just the simple resistance that the coil or circuit offers to the flow of d.c. Instead, it is the resistance that the coil or circuit offers to the flow of a.c., which rises with the frequency of the applied a.c. and is greater than the d.c. resistance.

Skin Effect. One reason why the a.c. resistance is greater than the d.c. resistance (except at very low frequencies) is because of the *skin effect*. To explain skin effect, it is necessary to remember what we know about the flow of d.c. in a conductor. In a d.c. circuit, free electrons flow at the same rate in all parts of the cross section, as in Fig. 16-11a. This is not so with a.c. As the frequency rises, more and more of the

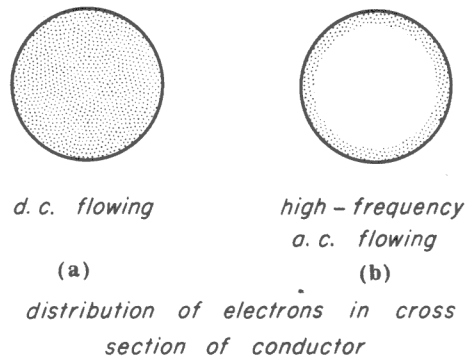


Fig. 16-11

electrons travel near the surface of the conductor and fewer and fewer travel in the center of the cross section of the conductor. (Fig. 16-11b). The resistance of a conductor depends partly on the area of the cross section. So, as the useful part of the cross section grows smaller, it's the same as if there were a smaller cross section. With a smaller effective cross section, resistance rises. At very high frequencies, solid conductors are not used; instead, conductors of hollow tubing, such as in Fig. 16-12, are used. In this way, the wire does not have a useless, non-current-carrying core. With the same amount of copper used to make a solid conductor, a pipe-like conductor of greater diameter can be made. Also, eddy currents are reduced. Thus, a.c. resistance is cut down, as described below. Another method of avoiding the increase in a.c. resistance, caused by skin effect, is the use, at standard radio broadcast frequencies, of wire made up of many fine strands. Such wire is called *Litzendraht* wire, which is usually shortened to just *Litz* wire. Each strand of such wire is insulated from the other, so that the many strands act as so many parallel conductors. Because each strand has a very small cross

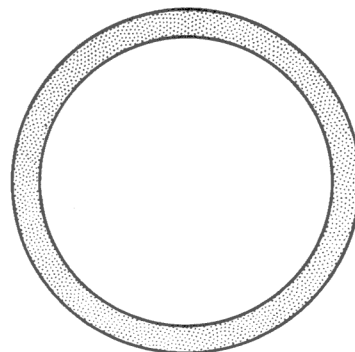


Fig. 16-12

section, there is little or no skin effect until the frequency of the applied voltage rises beyond the standard radio frequencies.

Eddy Currents. Another reason why the a-c resistance of a conductor is greater than the d-c resistance is because of eddy currents. Since these small currents cause a loss of power, they add to the total resistance of the circuit. The resistance due to skin effect and eddy currents rises with frequency. This resistance, added to the normal d-c resistance of the conductor, makes up the a-c resistance — the resistance used in figuring the Q of a coil or circuit.

Q of a Series-Tuned Circuit. At low frequencies, X_L rises faster than the a-c resistance. As a result, the Q rises as the frequency rises until a point is reached where the a-c resistance rises as rapidly as the inductive reactance. When this happens, the circuit Q remains about the same for a wide band of frequencies. Then the a-c resistance begins to rise more rapidly than does the inductive reactance, and the Q becomes less with further increases in frequency. The coils used in standard broadcast receivers are normally designed to have a Q that rises slightly at the low-frequency end of the tuning range, that remains level for most of the middle frequencies, and that falls slightly at the high-

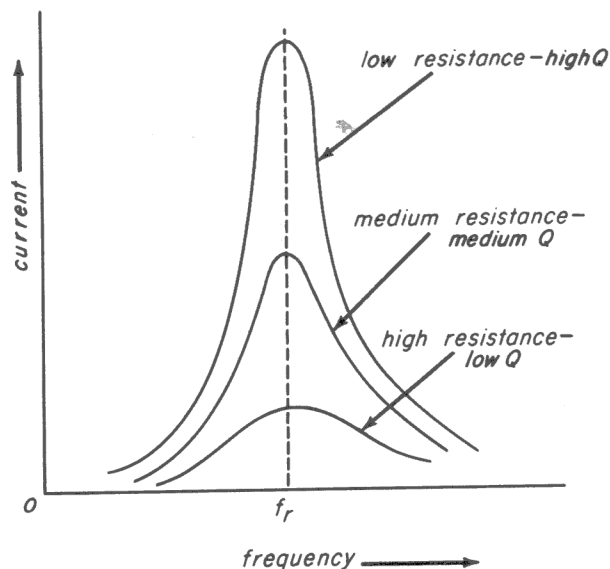


Fig. 16-13

frequency end. One reason why this is done is to produce a receiver that is *sensitive* across the entire broadcast band. The *sensitivity* of a receiver is a measure of its ability to pick up weak signals, to amplify them, detect them, and to reproduce them, in the form of sound, at a useful specified volume in loudspeaker. Normally, we don't want a receiver to be more sensitive at one end of the band than at the other.

However, the *selectivity* of a tuned circuit also depends on the Q . Selectivity is a measure of the ability of tuned circuits to choose one frequency and reject all others. As the curves in Fig. 16-13 show, the higher the Q , the greater is the selectivity; while the lower the Q (the higher the resistance), the lower is the selectivity and the wider is the band of frequencies passed. Notice that a very narrow band of frequencies is passed when the resistance is low, a wider band when the resistance is increased, and a still wider band when the resistance is high.

The bandpass of a series-tuned circuit is the number of cycles between the lowest frequency and the highest frequency passed, wherein the amplitude of current or voltage is 0.707 or more of the peak value of the current shown in the response curve. In the curve in Fig. 16-14, all of frequencies between f_1 and f_2 is said to be accepted or passed.

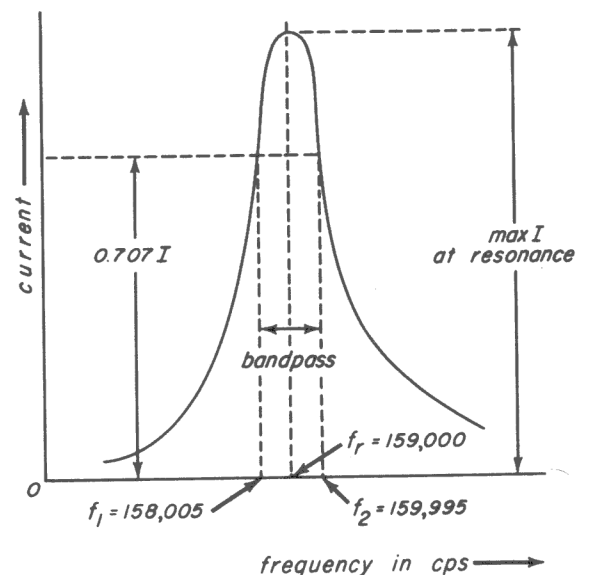


Fig. 16-14

The bandpass of a series-tuned circuit may be seen by looking at a response curve (such as in Fig. 16-14). It is also possible to calculate it by using the circuit Q . The formula used is:

$$BP = \frac{f_r}{Q_o}$$

where:

$$\begin{aligned} BP &= \text{bandpass in cps} \\ f_r &= \text{resonant frequency in cps} \\ Q_o &= \text{circuit } Q \end{aligned}$$

For example, if the Q of a series-resonant circuit is 80 and its resonant frequency is 1,590 kc, then:

$$\begin{aligned} BP &= \frac{f_r}{Q_o} \\ &= \frac{1,590,000}{80} \\ &= 19,875 \text{ cps} \end{aligned}$$

Resonant Rise of Voltage. It should be noted that, at resonance, the voltage across the inductor and the voltage across the capacitor are higher than the applied voltage. In formula form, this is stated:

$$E_L = E_C = QE_{\text{applied}}$$

This increase in voltage across the coil and capacitor is referred to as a Q resonant rise of voltage. As an example, if the Q of a series resonant circuit is 200 and the applied voltage is 10 volts, then E_L will be 2,000 volts and E_C will also be 2,000 volts.

If you are interested in the derivation, the formula is derived in the appendix to this lesson.

L/C Ratio. Another factor that affects the selectivity of a tuned circuit is the ratio of L to C . In the series resonance problems, we found that a 50- μ h inductor resonated with a 200- μ mf capacitor

at 1,590 kc. The formula, you remember, is:

$$f^2 = \frac{25,300 \times 10^6}{LC}$$

We found that the product of L (50 μ h) and C (200 μ mf) was 10,000. Any combination of L (in μ h) and C (in μ mf) that equals 10,000 resonates at the same frequency. In other words, 10 μ h and 1,000 μ mf, 20 μ h and 500 μ mf, 100 μ h, and 100 μ mf, etc. all resonate at 1,590 kc. It is found, however, in a series-resonant circuit, that the higher the L/C ratio, the greater is the selectivity. Therefore, a 200- μ h inductor and a 50- μ mf capacitor would produce a more selective series-resonant circuit than a 50- μ h inductor and a 200- μ mf capacitor.

Tuning Series-Resonant Circuits. We have been discussing fixed values of inductance and capacitance needed to obtain resonance at some frequency. In a radio receiver, we normally want circuits that will resonate at different frequencies from 550 to 1,600 kc. This may be done in two ways: either by using a fixed inductor and a variable capacitor or by using a fixed capacitor and a variable inductor. Suppose that we have a 200- μ h inductor that we want to resonate at 550 kc. We can find the value of the capacitor needed by using the formula:

$$\begin{aligned} C &= \frac{25,300 \times 10^6}{f^2 L} \\ &= \frac{25,300 \times 10^6}{550^2 \times 200} \\ &= \frac{25,300 \times 10^6}{302,500 \times 200} \\ &= \frac{25,300 \times 10^6}{60.6 \times 10^6} \\ &= 418 \mu\text{mf} \end{aligned}$$

Using the same value of inductance, we can find the amount of capacitance needed at 1,600 kc. The calculations are made in the same manner as before and the value is

found to be $49.4 \mu\mu\text{f}$. So, to make it possible to resonate a $200\text{-}\mu\text{h}$ inductor to any frequency between 550 and 1,600 kc, we need a capacitor that varies from 49.4 to $418 \mu\mu\text{f}$. When we use such a capacitor to change the resonant frequency, we call it a *tuning capacitor* and say that we are *tuning* the circuit with it.

As we have said, the circuit may be tuned by varying the inductance and keeping the capacitor to one fixed value. Let's see what the inductance range must be to tune a $100\text{-}\mu\mu\text{f}$ capacitor from 550 kc to 1,600 kc. We use the formula:

$$\begin{aligned} L &= \frac{25,300 \times 10^6}{f^2 C} \\ &= \frac{25,300 \times 10^6}{550^2 \times 100} \\ &= \frac{25,300 \times 10^6}{302,500 \times 100} \\ &= \frac{25,300 \times 10^6}{30.25 \times 10^6} \\ &= 836 \mu\text{h} \end{aligned}$$

We find the amount of inductance needed to resonate the capacitor at 1,600 kc. The calculations are done in the same manner as before. The value is $99 \mu\text{h}$. So, to make it possible to tune a $100\text{-}\mu\mu\text{f}$ capacitor to any frequency between 500 and 1,600 kc, we need an inductor that varies between $836 \mu\text{h}$ and $99 \mu\text{h}$. Notice that the inductance decreases as the frequency increases.

Variable Inductors. You know that the inductance of a coil may be varied by increasing or decreasing the number of turns that make it up (assuming that all turns are evenly wound). In practical radio and television, the coil must be wound with enough turns to provide the highest value of inductance needed. Then the inductance may be decreased by using fewer turns. This method of changing inductance is used in the coil

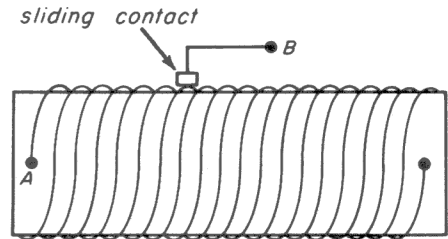


Fig. 16-15

shown in Fig. 16-15. One fixed terminal, A, is connected to a sliding contact that may be moved from turn to turn. By varying the position of the sliding contact, the turns necessary to produce a certain value of inductance may be obtained between the two terminals.

You know, too, that we can vary the inductance of a coil by varying the insertion of the core material in the coil. If we insert an iron core partly in a coil, as in Fig. 16-16a, the inductance is increased. If the iron core is inserted still farther into the coil, as in Fig. 16-16b, the inductance increases. This method is commonly used today in tuning coils for radio and television receivers. A core is made of powdered iron that is mixed with some plastic material. The core is formed into a shape such as that shown in Fig. 16-16c, and attached to a threaded screw. When this powdered-iron slug is placed within a tuning coil, the inductance of the coil is varied by changing the position of the slug with an alignment tool.

16-3. PARALLEL A-C CIRCUITS

Until now, we have discussed a-c circuits where combinations of R , L , and C were con-

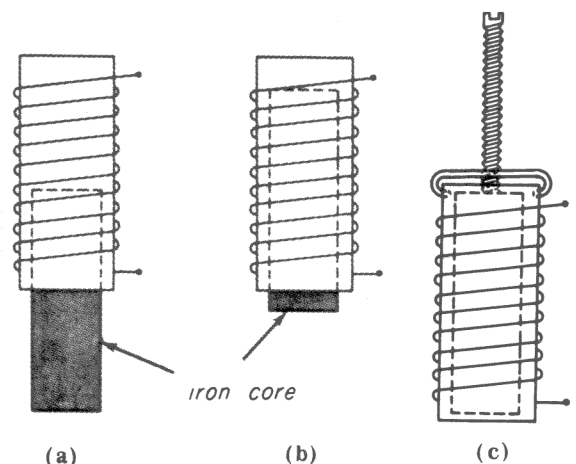


Fig. 16-16

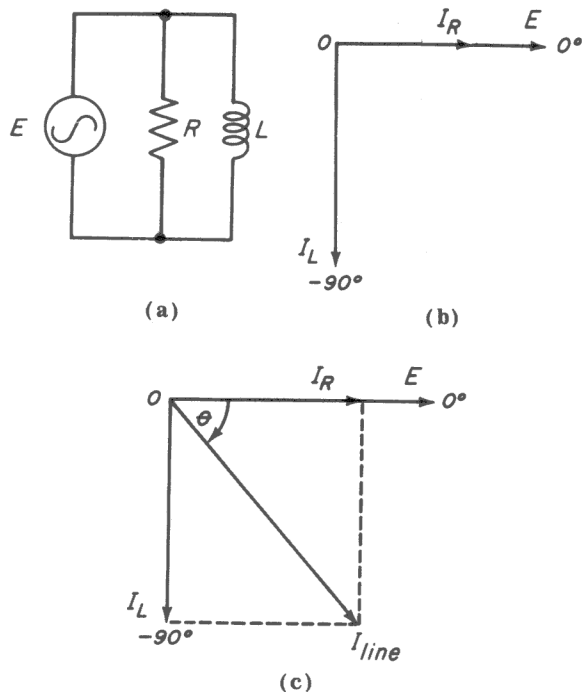


Fig. 16-17

nected in series. Now, let's see what happens when we connect them in parallel.

The simple combination of a resistor, inductor, and a-c voltage source connected in parallel is shown in Fig. 16-17a. Because both R and L are connected in shunt with the voltage source, E_R and E_L are in phase with the voltage, E , supplied by the generator. We know that the current flowing through R is in phase with the voltage, because there is no phase shift in a purely resistive circuit. However, the current in a purely inductive circuit lags the voltage by 90 degrees. So, we can draw a current vector showing these relationships, as in Fig. 16-17b. The voltage, being in phase with the resistive current, is shown as the reference (0°). This causes us to draw the inductive current as a vector of a certain magnitude and at an angle of -90 degrees. To find the line current, we can complete the vector addition, as in Fig. 16-17c. From this you can see that:

$$I_{line} = \sqrt{I_R^2 + I_L^2}$$

Once we know the line current, we can find the impedance of the circuit by using Ohm's law for a.c.:

$$Z = \frac{E}{I}$$

where:

Z = impedance of the parallel circuit

E = applied voltage

I = line current

The phase angle can be found by finding the cosine θ :

$$\cosine \theta = \frac{I_R}{I_{line}}$$

and then finding the angle in the cosine table.

Figure 16-18a shows a resistor, capacitor, and a-c voltage source connected in parallel. In this circuit, E_R , E_C , and I_R are all in phase. But, as you know, the current in a purely capacitive circuit leads the voltage by 90 degrees. So, in the vector (Fig. 16-18b) we draw I_C as a vector of 90 degrees (above the reference line). To find the line current, we complete the vector addition, as in Fig. 16-18c. If we have the values of I_R and I_C , we can find the line current with this formula:

$$I_{line} = \sqrt{I_R^2 + I_C^2}$$

When pure inductance and pure capacitance are connected in parallel across a voltage

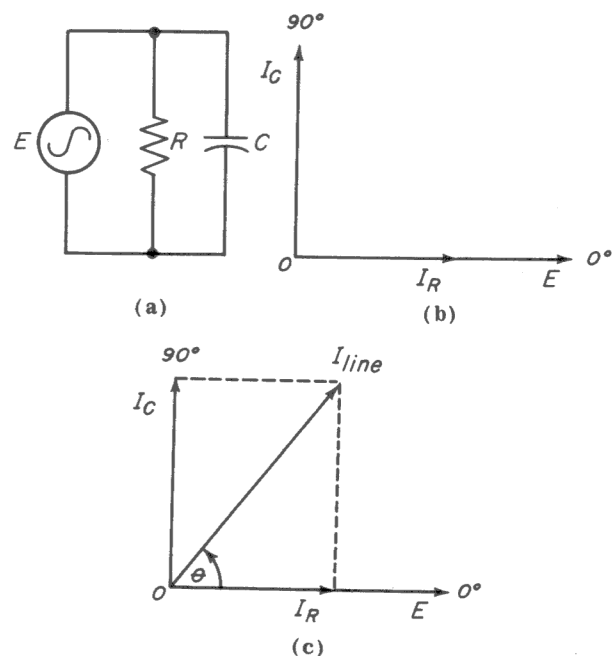


Fig. 16-18

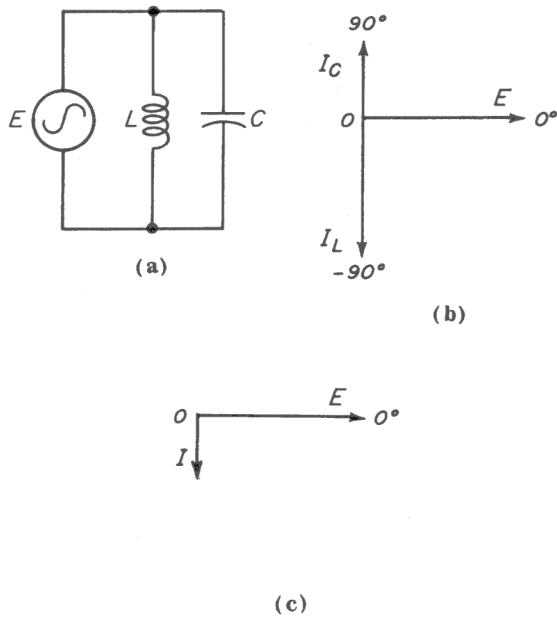


Fig. 16-19

source, as in Fig. 16-19a, E_L and E_C are in phase with the line voltage. I_L lags the line voltage by 90 degrees; I_C leads the line voltage by 90 degrees. Hence I_L and I_C are 180 degrees out of phase. Figure 16-19b shows the current vector for such a circuit. Because we are assuming that these are pure reactances, each inductive ampere cancels each capacitive ampere. Therefore, we can subtract one from the other (whichever is the lesser from the greater). If the inductive current is greater than the capacitive current, as in Fig. 16-19b, we can complete the vector addition, as in Fig. 16-19c. After subtracting I_C from I_L , we find that the remaining reactive current is the line current, which lags the voltage by 90 degrees. So, we can see that the circuit is reactive and acts like a pure inductance. When the capacitive current is greater than the inductive current, the remainder will be a leading current. The circuit will be reactive and act like a pure capacitance. From these two possibilities, we see that when the inductive current is greater than the capacitive current, the circuit is inductive, and when the capacitive current is greater than the inductive current, the circuit is capacitive.

16-4. PARALLEL RESONANCE

Let's see what happens when the reactive currents are equal — when $I_L = I_C$, as in Fig. 16-20a. This can happen only when the

opposition to current flow in the inductive branch equals the opposition to current flow in the capacitive branch; in other words, when $X_L = X_C$. Figure 16-20b shows the relationship between the reactive currents and the applied voltage. Because $X_L = X_C$, $I_L = I_C$. These currents, being 180 degrees out of phase, cancel each other; so there is no line current. The circuit, therefore, acts like a circuit of infinite (limitless) impedance. We call this condition *parallel-resonance*.

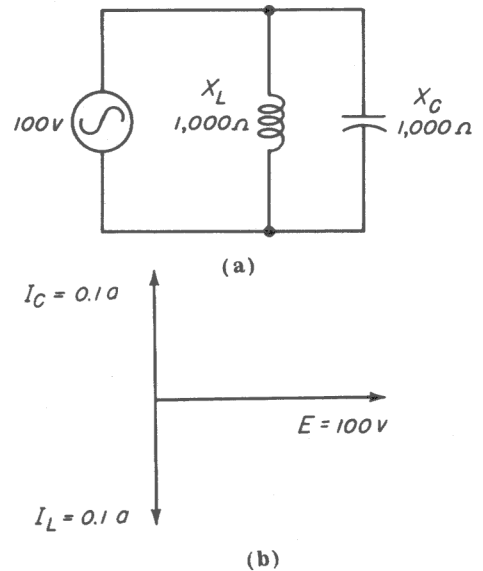


Fig. 16-20

We know that practical coils have resistance. Figure 16-21a shows a practical parallel-resonant circuit, with resistance shown in series with the coil in the inductive branch. This resistance represents the resistance of the coil. Referring to the vectors shown in Fig. 16-21b, we find that the inductive current is not exactly 180 degrees out of phase with the capacitive current in the capacitive branch, since the inductive current lags the voltage by less than 90 degrees.

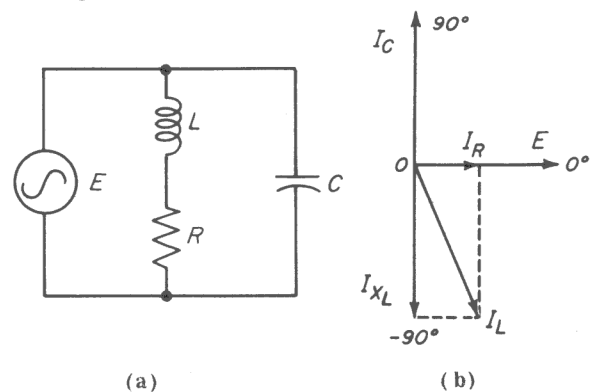


Fig. 16-21

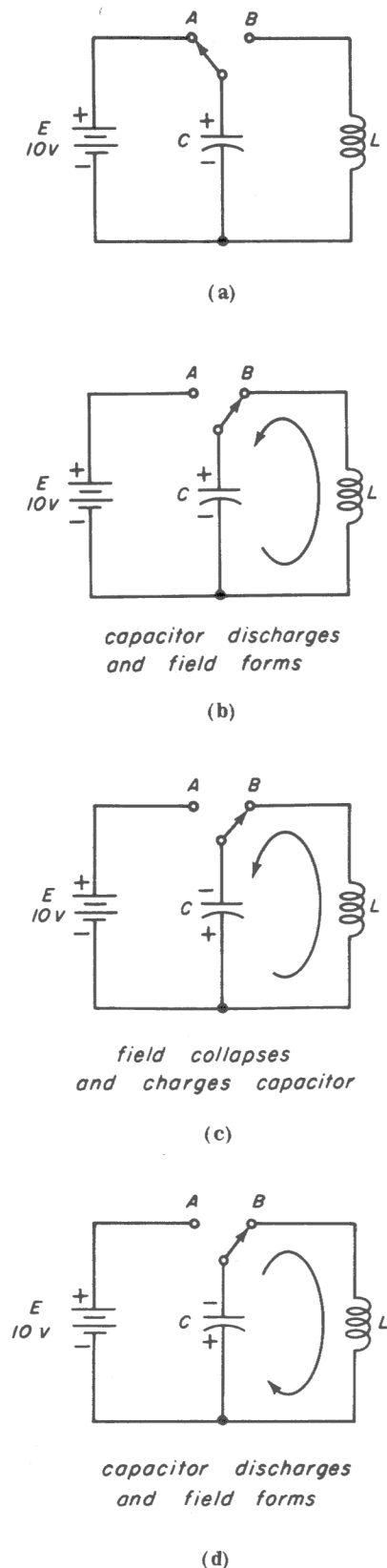


Fig. 16-22

Let's see what effect the small resistance of the inductive branch has upon the parallel resonant circuit, or *tank* circuit, as it is sometimes called. For a moment, we'll assume that the circuit is the ideal tank circuit, one without resistance. Suppose we connect the capacitor and inductor of our tank circuit to a switch and d-c voltage source, as shown in Fig. 16-22a. With the switch in position A, you can see that the capacitor will be charged by the battery. When the capacitor is charged, we throw the switch to position B, as in Fig. 16-22b. With this action, the capacitor discharges through the coil, L , which produces a momentary current that causes an electromagnetic field to be set up around the coil. As soon as the capacitor's discharge current stops flowing, the magnetic field collapses, which produces a current in the same direction as the capacitor-discharge current. This produces a charge on the capacitor opposite in polarity to the original charge. When the field is completely collapsed, the charging current stops, which causes the capacitor to discharge again through the coil. This time, however, the discharge current is in a direction opposite to the original discharge current. Again a field is formed in the coil, and then the field collapses and charges the capacitor in the original direction. From the drawings in Fig. 16-22b, c, and d, you can see that current flows first in one direction and then in the other. In producing a magnetic field in the coil, the capacitor transfers power to the coil, which, in turn, transfers the power back to the capacitor. In a tank circuit without resistance, this shifting of power back and forth between the capacitor and coil would continue indefinitely. However, as you know, there is always some resistance in the inductive branch. This resistance produces a power loss. Each time the capacitor discharges through the coil, a little power is used up by the resistance of the coil. This reduces the amount of charge on the capacitor. After a while, all of the power is used up in the coil and the capacitor receives no further charge.

To keep the current flowing back and forth between the capacitor and coil, we need some method of supplying the amount of power lost in the coil. We might do this by giving the capacitor a little power from the battery to

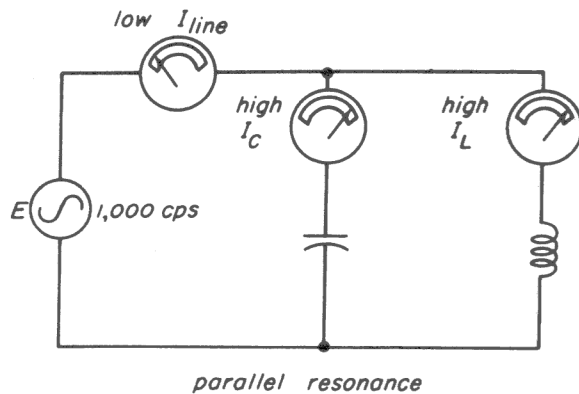


Fig. 16-23

complete the charge each time the capacitor receives power from the coil. This would cause a small amount of current to flow from the battery during each charging cycle.

When a.c. of the resonant frequency is applied to the circuit, as in Fig. 16-23, reactive current flows back and forth between the capacitor and the coil, at the rate of the resonant frequency. Meters inserted in the inductive and capacitive branches would show that the reactive current is high in each branch, while a meter in the line between the voltage source and the tank circuit would show a very small line-current reading. This small reading would indicate that the generator is supplying the small amount of power lost in the inductive branch. Thus, we can see that the line current of a parallel-resonant circuit is very small and due only to the slight losses in the tank circuit.

In the case of the parallel-tuned circuits, the current in either the capacitor or the coil branch is higher than the line current. In formula form:

$$I_C = I_L = Q I_{\text{line}}$$

In effect, the circulating tank current is Q times as high as the line current.

At resonance, the line current may be found by this formula:

$$I_{\text{line}} = \frac{E}{Z}$$

Because there is some line current flowing in a parallel-resonant circuit, the circuit does not have infinite impedance (as it would if there were no resistance). The impedance of a resonant tank depends on the Q of the coil, which is found by the formula:

$$Q = \frac{X_L}{R}$$

The impedance may then be found by the formula:

$$Z = Q X_L$$

So, if the Q of the coil is 125, the impedance Z is equal to 125 times the inductive (or capacitive) reactance. If the inductive reactance is 1,000 ohms, the impedance is 125,000 ohms. Maximum impedance and minimum current occur only at resonance in a parallel-tuned circuit.

The Q of a series-resonant circuit is, for all practical purposes, equal to the Q of the coil. As you know, the higher the Q_0 , (Q_0 is the symbol for the Q of the circuit), the narrower is the bandpass; while the lower the Q_0 , the broader is the bandpass. The Q_0 , in turn, depends on the series resistance, which is usually due to the coil; as the resistance increases, the Q_0 decreases. The same is true for a parallel-resonant circuit. The Q is found in the same way as for a series-resonant circuit, and the series resistance has the same effect as it would have in a series-resonant circuit. So, one way to broaden the bandwidth of a parallel tuned circuit is to use low- Q coils or to add resistance in series with either the inductive or capacitive branch.

The selectivity of a parallel-resonant circuit depends, as does that of a series-resonant circuit, on the Q of the circuit. To keep the selectivity high, the losses in the circuit must be kept to a minimum. Thus the series resistance, represented by R in Fig. 16-21, must be kept low; and the shunt resistance, represented by R_S in Fig. 16-24, must be kept as high as possible or eliminated.

The selectivity of a parallel-resonant circuit may be changed by placing a resistor in parallel with the tank circuit, as in Fig.

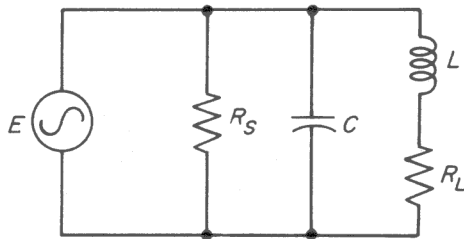


Fig. 16-24

16-24. In such a circuit, the lower the shunt resistance, R_S , the broader is the bandpass. The Q of such a circuit is found with this formula:

$$Q = \frac{R_S}{X_L}$$

where:

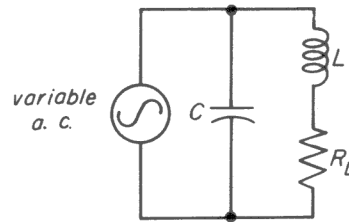
Q = parallel-resonant circuit Q

R_S = resistance of shunt resistor in ohms

X_L = inductive reactance at resonance

The bandpass of a parallel-resonant circuit is equal to the resonant frequency divided by the circuit Q , as it is for the series-resonant circuit.

Until now, we have considered the characteristics of a parallel-tuned circuit only at resonance. Figure 16-25a shows a parallel-tuned circuit that resonates at 1,000 kc connected to a variable-frequency a-c supply. To frequencies below resonance (1,000 kc), the circuit acts like an inductor because the reactance of the coil is less than that of the capacitor, so the inductive branch draws more current than the capacitive branch, as shown in Fig. 16-25b and c. The difference between the current in the capacitive branch and that in the inductive branch is greater than the difference at resonance, which causes an increase in the line current. To frequencies above resonance, the circuit acts like a capacitor because the reactance of the capacitor at these higher frequencies is less than that of the inductor. This causes the current in the capacitive branch to exceed the current in the inductive branch, which causes an increase in line current over that at resonance. So, a parallel-tuned circuit acts inductive to frequencies below res-



resonant frequency equals 1,000 kc

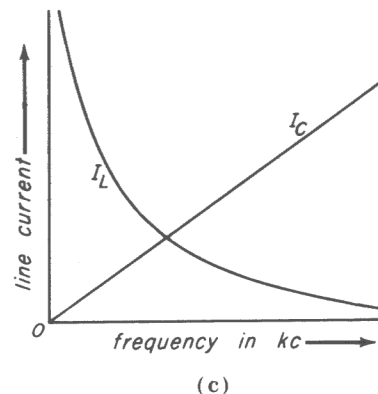
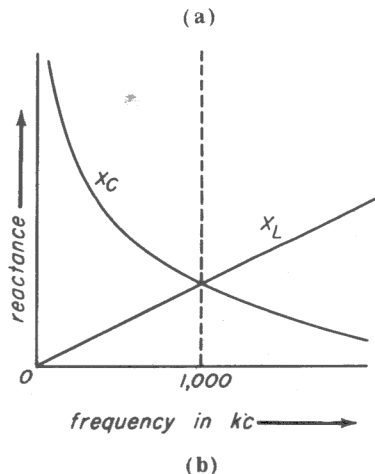


Fig. 16-25

onance and capacitive to frequencies above resonance, and in each case the line current increases over the line current at resonance.

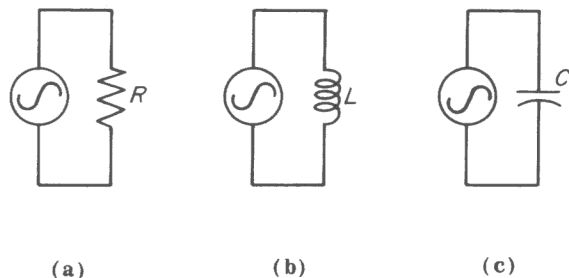


Fig. 16-26

TABLE A - COMPARISON OF SERIES AND PARALLEL TUNED CIRCUITS

Series Tuned	Parallel Tuned
1. L and C are in series.	1. L and C are in parallel.
2. Resonance occurs when $X_L = X_C$.	2. Resonance occurs when $X_L = X_C$.
3. Z is minimum at resonance and is equal to R of the circuit.	3. Z is maximum at resonance and is equal to QX_L .
4. I_{line} is maximum at resonance and equal to E/Z .	4. I_{line} is minimum at resonance and equal to E/Z .
5. Circuit acts like a resistor of low value, has power factor of 1, and I_{line} and E are in phase.	5. Circuit acts like a resistor of high value, has power factor of 1, and I_{line} and E are in phase.
6. $I_C = I_L = I_{\text{line}}$.	6. $E_L = E_C = E_{\text{line}}$.
7. At resonance, E_L and E_C are approximately equal and almost 180 degrees out of phase.	7. At resonance, I_L and I_C are approximately equal and almost 180 degrees out of phase.
8. Circuit Q is approximately equal to coil Q and is equal to X_L/R .	8. Circuit Q is approximately equal to coil Q and is equal to X_L/R except with shunt resistor. Then $Q = R/X_L$.
9. Bandpass of a series resonant circuit is equal to f_r/Q_o .	9. Bandpass of a parallel resonant circuit is equal to f_r/Q_o .
10. Selectivity of a series-resonant circuit depends on circuit Q ; the lower the series resistance is, the greater is the selectivity.	10. Selectivity of a parallel-resonant circuit depends on circuit Q ; the <i>higher</i> the shunt resistance and the <i>lower</i> the series resistance, the greater is the selectivity.
11. For frequencies below resonance, the circuit is capacitive and the line current is leading; for frequencies above resonance, the circuit is inductive and the line current is lagging.	11. For frequencies below resonance, the circuit is inductive and the line current is lagging; for frequencies above resonance, the circuit is capacitive and the line current is leading.

16-5. DISTRIBUTED AND LUMPED CONSTANTS

We call a resistor, an inductor, or a capacitor a *lumped* constant because each is a circuit component that possesses a particular circuit property that is concentrated in one place in some desirable amount. This means that a resistor is made for the purpose of offering lumped resist-

ance, that an inductor is made to offer lumped inductance, and that a capacitor is made to offer lumped capacitance. So, we think of a circuit like that shown in Fig. 16-26a as being a resistive circuit, which it is for the most part. In the same way, we think of a circuit like that in Fig. 16-26b as being inductive and one like that in Fig. 16-26c as being capacitive. Yet a purely resistive, inductive, or capacitive

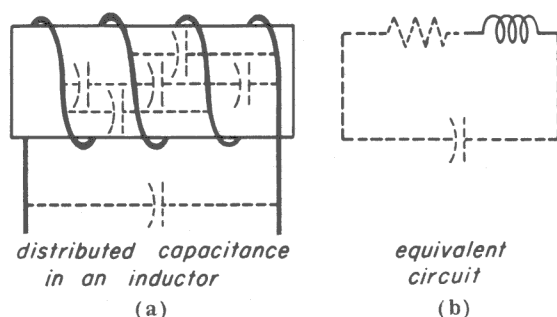
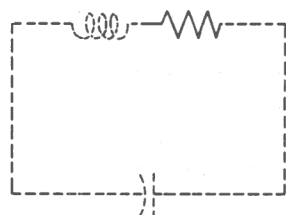


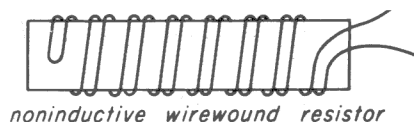
Fig. 16-27

a-c circuit is not possible. Every a-c circuit possesses each of the three circuit properties in some amount, whether large or small. For example, in addition to its lumped inductance, the coil shown in Fig. 16-27a has resistance due to length, cross section, and kind of wire from which it is wound. This you already know. You may be surprised to learn that it also has capacitance. Two conductors separated by a nonconductor act as plates of a capacitor. So, capacitance exists between one turn and the next. Capacitance also exists between turns that are separated by other turns, between end terminals, and between each turn and ground. Such capacitance is called *distributed* capacitance because it is not lumped in one fixed unit. The resistance of an inductor may be considered to act the same as a resistor with lumped resistance of the same value, connected in series with the inductor, and the distributed capacitance may be considered to act the same as a capacitor with lumped capacitance of the same value connected in parallel with the inductor, as shown by the dotted lines in Fig. 16-27b. The resistance and distributed capacitance of an inductor may have no practical effect at low frequencies and thus may be ignored. But at higher frequencies, the distributed capacitance and resistance of an inductor may cause serious losses in energy and may even cause the inductor to act improperly.



equivalent circuit of a resistor

Fig. 16-28



noninductive wirewound resistor

Fig. 16-29

You know that a simple conductor in an a-c circuit has inductance; so an insulated composition resistor has a small amount of inductance due to its wire leads. This inductance may be considered to be in series with the resistance, and any stray capacitance that exists because of the same leads may be considered to be in parallel, as shown in Fig. 16-28. The distributed capacitance is greater if the resistor is wirewound. Then the capacitance is distributed in the same way as for an inductor. A wirewound resistor has more inductance than an insulated composition resistor because of the windings of the wire from which it is made. To reduce the distributed inductance of a wirewound resistor, it may be wound as shown in Fig. 16-29. Half of the turns of resistance wire are wound in one direction and the other half are wound in the opposite direction. In this way, the counter emf of one half the winding is opposite to the counter emf of the second half of the winding. This causes the counter emf's to cancel out and produce a minimum of inductance effects.

A capacitor used in an a-c circuit has a small amount of resistance in its leads and connections. Paper capacitors may have inductance due to the turns of metal foil from which they are made. This inductance may be shorted out by crimping the ends of each foil plate together (as explained in Theory Lesson 15). However, even if this is done, some inductance will remain due to the wire leads. The resistance and the distributed inductance may be considered to be in series with the capacitance of the capacitor, as shown in the equivalent circuit (Fig. 16-30a). If there is any leakage in the dielectric or in the capacitor casing, this resistance may be considered to be in parallel, as in Fig. 16-30b. When good-quality capacitors are used, the resistance and distributed inductance are so very small that they may be ignored in most of our calculations. However, when the frequency of the applied a.c. becomes very high, even

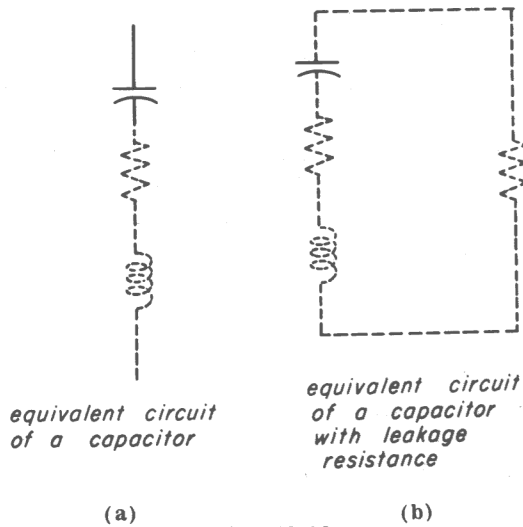


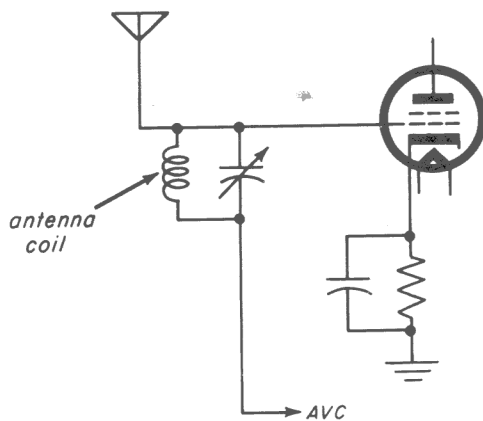
Fig. 16-30

a small amount of resistance or inductance becomes very important.

For the most part, distributed capacity and inductance have little effect at standard broadcast frequencies, but at FM and TV frequencies, they are very important. For example, in designing tuned circuits for very high frequencies, engineers have to figure in the distributed capacitance of a coil or the distributed inductance of a capacitor. If they don't, the tuned circuits act improperly.

16-6. PRACTICAL RESONANT CIRCUITS

Circuits that resonate at one frequency or that may be tuned to a certain band of



a parallel-resonant circuit

Fig. 16-31

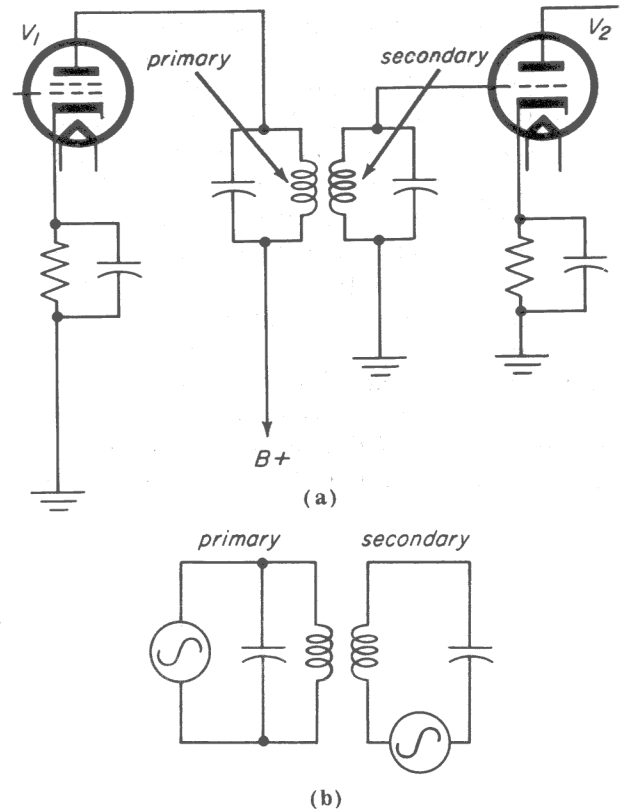


Fig. 16-32

frequencies are used in all radio and television receivers. For example, the antenna coil that receives the incoming radio signal from the antenna, as shown in Fig. 16-31, is tuned by a variable capacitor. Such a circuit, because it is directly connected to the source of voltage (the antenna), is a parallel-resonant circuit. Another example of a parallel-resonant circuit is shown in Fig. 16-32a. In this case, there is a transformer connecting the output of one tube into the input of another tube. The source of voltage is the plate circuit of tube V_1 . Therefore, the primary is a parallel-resonant circuit because it is directly connected to the voltage source. The secondary of the transformer, however, is a series-resonant circuit because the voltage is induced (by the primary) into the secondary winding. The simplified drawing of the tuned circuits is shown in Fig. 16-32b. The primary is shown connected in shunt with the voltage source, while the secondary is shown with the voltage source in series with the capacitor and coil. In other lessons, we will use this method of identifying parallel- and series-resonant circuits in schematic drawings.

How to Identify Resonant Circuits. Sometimes the question arises: "Is this a series- or parallel-resonant circuit?" However, it is really not as difficult to tell one from the other as it might seem. Use this simple way and you'll have no trouble. We know that parallel-tuned circuits are connected in parallel and series-tuned circuits in series with the voltage source. So, first, we look for the voltage source, which, in radio receivers, may be an antenna, the plate circuit of an electron tube, and circuits from which voltages are induced. Next we look to see if the tuned circuit is connected in parallel with the voltage source or

is in series with it. For all practical purposes, we can say that if the tuned circuit has voltage induced into it, such as in the secondary of an r-f or i-f transformer, the tuned circuit is series resonant. If the tuned circuit is connected, directly or through a capacitor, to the voltage source, it is parallel resonant.

While most radio receivers are tuned by variable capacitors that are controlled by the tuning knob, there are some receivers that have fixed capacitors and are tuned by variable inductors of the type discussed earlier in this lesson.



APPENDIX

1. RESONANT FREQUENCY

If you want to know how the resonant frequency formula is derived, here are the steps:

$$X_L = X_C$$

$$X_L = 2\pi f L$$

$$X_C = \frac{1}{2\pi f C}$$

Therefore:

$$2\pi f L = \frac{1}{2\pi f C}$$

Gathering terms, we find:

$$f^2 = \frac{1}{4\pi^2 L C}$$

Taking the square root of both sides, we get:

$$f = \frac{1}{2\pi \sqrt{L C}}$$

where:

f = resonant frequency in cycles per second

L = inductance in henrys

C = capacitance in farads

We can go further and derive the practical resonance formula:

$$f^2 = \frac{25,300 \times 10^6}{L C}$$

where:

f^2 = resonant frequency in kilocycles, squared

L = inductance in microhenrys

C = capacitance in micromicrofarads

These are the steps:

$$f^2 = \frac{1}{4\pi^2 L C}$$

We divide the numerator (1) by $4\pi^2$, therefore:

$$f^2 = \frac{0.0253}{L C}$$

Then we change the units so that f is in kc , L is in μh , and C is $\mu\mu f$:

$$(f \times 10^3)^2 = \frac{0.0253}{L \times 10^{-6} C \times 10^{-12}}$$

$$f^2 \times 10^6 = \frac{0.0253 \times 10^{18}}{L C}$$

Dividing both sides of the equation by 10^6 , we get:

$$f^2 = \frac{0.0253 \times 10^{12}}{L C}$$

$$f^2 = \frac{25,300 \times 10^6}{L C}$$

To find L when the other factors are known, the formula is:

$$L = \frac{25,300 \times 10^6}{f^2 C}$$

And to find C , the formula is:

$$C = \frac{25,300 \times 10^6}{f^2 L}$$

2. A-C SERIES CIRCUIT PROBLEMS

As shown in the diagram, a voltage source E is shown in series with inductance L , resistance R , and capacitance C . $E = 100$ volts, $R = 100$ ohms, $L = 15.9$ millihenrys, $C = 1.59$ microfarads, and the frequency of the applied voltage is 500 cycles per second. Let us find X_L , X_C , Z , I_{line} , E_{XL} , E_{XC} ,

E_R , cosine θ , phase angle, P_{apparent} , and P_{true} . To find X_L , we use the formula:

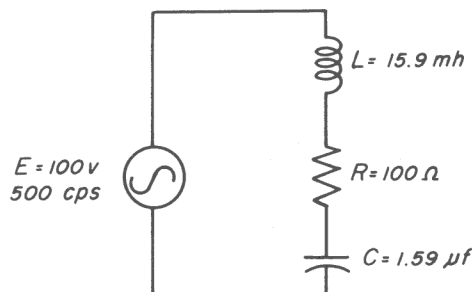
$$\begin{aligned} X_L &= 2\pi f L \\ &= 6.28 \times 500 \times 15.9 \times 10^{-3} \\ &= 100 \times 500 \times 10^{-3} \\ &= 50 \text{ ohms} \end{aligned}$$

To find X_C we use the formula:

$$\begin{aligned} X_C &= \frac{1}{2\pi f C} \\ &= \frac{1}{6.28 \times 500 \times 1.59 \times 10^{-6}} \\ &= \frac{1}{10 \times 500 \times 10^{-6}} \\ &= \frac{1}{5,000 \times 10^{-6}} \\ &= \frac{1}{5 \times 10^{-3}} \\ &= \frac{1,000}{5} \\ &= 200 \text{ ohms} \end{aligned}$$

We next find Z :

$$\begin{aligned} Z &= \sqrt{R^2 + (X_L - X_C)^2} \\ &= \sqrt{100^2 + (50 - 200)^2} \\ &= \sqrt{100^2 + (-150)^2} \\ &= \sqrt{10,000 + 22,500} \\ &= \sqrt{32,500} \\ &= 180 \text{ ohms (approx)} \end{aligned}$$



The line current comes next:

$$\begin{aligned} I_{\text{line}} &= \frac{E}{Z} \\ &= \frac{100}{180} \\ &= 0.555 \text{ amps} \end{aligned}$$

E_{XL} may then be found:

$$\begin{aligned} E_{XL} &= I \times X_L \\ &= 0.555 \times 50 \\ &= 27.8 \text{ volts} \end{aligned}$$

E_{XC} follows:

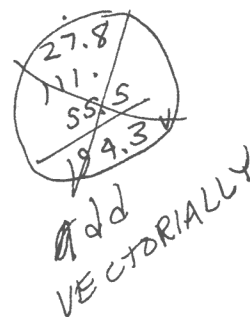
$$\begin{aligned} E_{XC} &= I \times X_C \\ &= 0.555 \times 200 \\ &= 111 \text{ volts} \end{aligned}$$

E_R comes next:

$$\begin{aligned} E_R &= I \times R \\ &= 0.555 \times 100 \\ &= 55.5 \text{ volts} \end{aligned}$$

Cosine θ is found:

$$\begin{aligned} \text{Cosine } \theta &= \frac{R}{Z} \\ &= \frac{100}{180} \\ &= 0.555 \end{aligned}$$



The phase angle may be found in the cosine table. There we find that 0.555 is the cosine of an angle of 56 degrees (approximately). So, since the circuit is capacitive, the phase angle is -56 degrees; that is, the voltage lags the current by 56 degrees.

The apparent power is:

$$\begin{aligned} P_{\text{apparent}} &= E \times I \\ &= 100 \times 0.555 \\ &= 55.5 \text{ VA} \end{aligned}$$

The true power is:

$$\begin{aligned} P_{\text{true}} &= P_{\text{apparent}} \times \cosine \theta \\ &= 55.5 \times 0.555 \\ &= 30.8 \text{ watts} \end{aligned}$$

It is possible to derive the following formula:

$$E_L = E_C = QE_{\text{applied}}$$

The current flow in a series circuit comprised of L , C , and R is:

$$I = \frac{E_{\text{applied}}}{\sqrt{R^2 + (X_L - X_C)^2}}$$

At resonance, $X_L = X_C$, therefore:

$$I = \frac{E_{\text{applied}}}{R}$$

Since

$$E_L = I X_L, \text{ then}$$

$$E_L = \frac{E_{\text{applied}}}{R} \times X_L$$

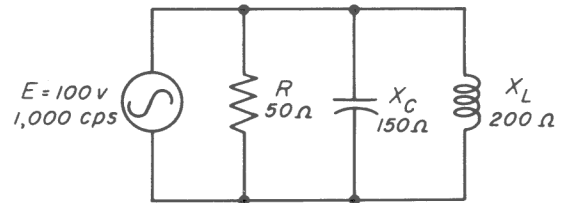
Since

$$Q = \frac{X_L}{R}$$

$$E_L = Q E_{\text{applied}}$$

3. PARALLEL A-C CIRCUIT PROBLEMS

A circuit containing R , L , and C in parallel with the supply voltage is shown below.



We know that the voltage in each branch is the same. The currents, however, differ in value and phase. We can calculate the current in each branch by using Ohm's law. For example:

$$\begin{aligned} I_R &= \frac{E}{R} \\ &= \frac{100}{50} \\ &= 2 \text{ amps} \end{aligned}$$

The inductive reactive current may be found in a like manner:

$$I_{X_L} = \frac{E}{X_L} = \frac{100}{200} = 0.5 \text{ amp.}$$

The current in the capacitive branch is:

$$\begin{aligned} I_{X_C} &= \frac{E}{X_C} \\ &= \frac{100}{150} \\ &= 0.67 \text{ amp.} \end{aligned}$$

The line current may be found by using the formula:

$$\begin{aligned} I_{\text{line}} &= \sqrt{I_R^2 + (I_{X_L} - I_{X_C})^2} \\ &= \sqrt{2^2 + (0.5 - 0.67)^2} \\ &= \sqrt{2^2 + (-0.17)^2} \\ &= \sqrt{4 + 0.03} \\ &= \sqrt{4.03} \\ &= 2.01 \text{ amps} \end{aligned}$$

The impedance Z may be found by using Ohm's law for a-c:

$$Z = \frac{E}{I}$$

$$= \frac{100}{2.01}$$

$$= 50 \text{ ohms (approx)}$$

Power for parallel a-c circuits is found in the same way as for series a-c circuits. For that reason, no practice problems for power are given here.

4. PRACTICE PROBLEMS

The problems that follow are for your practice, if you wish to do them. The answers will be found at the end of this part of the lesson.

Series Problems

1. $E = 200 \text{ v}$, $f = 60 \text{ cps}$, $R = 50 \text{ ohms}$, $L = 100 \text{ mh}$, $C = 40 \text{ } \mu\text{f}$. Find X_L , X_C , Z , I , E_{XL} , E_{XC} , E_R , phase angle, cosine θ , P_{app} , and P_t .
2. $E = 10 \text{ v}$, $f = 100 \text{ kc}$, $L = 500 \text{ } \mu\text{h}$, $C = 4,000 \text{ } \mu\text{f}$, $R = 10 \text{ ohms}$. Find X_L , X_C , Z , I , E_{XL} , E_{XC} , E_R , phase angle, cosine θ , P_{app} , and P_t .

Parallel Problems

1. In a parallel circuit such as that shown above, $E = 500 \text{ v}$, $f = 120 \text{ cps}$, $L = 4 \text{ henrys}$, $C = 0.5 \text{ } \mu\text{f}$, and $R = 20,000 \text{ ohms}$. Find X_L , X_C , I_{XC} , I_R , I_{line} , and Z .
2. In the same type of circuit, $E = 5 \text{ v}$, $f = 100 \text{ kc}$, $L = 10 \text{ mh}$, $C = 400 \text{ } \mu\text{f}$, and $R = 1,500$. Find X_L , X_C , I_{XL} , I_{XC} , I_{line} , and Z .

Resonant Frequency Problems

1. If $L = 15.9 \text{ mh}$ and $C = 1.59 \text{ } \mu\text{f}$, what is the resonant frequency?

2. If $L = 500 \text{ } \mu\text{h}$ and $C = 50 \text{ } \mu\text{f}$, what is the resonant frequency?
3. If $L = 100 \text{ } \mu\text{h}$, what value of C is needed to resonate at $1,500 \text{ kc}$?
4. If $L = 260 \text{ } \mu\text{h}$, what value of C is needed to resonate at 500 kc ?
5. If $L = 1.5 \text{ } \mu\text{h}$ and $C = 35 \text{ } \mu\text{f}$, what frequency will they resonate at?
6. If $L = 30 \text{ } \mu\text{h}$ and $C = 100 \text{ } \mu\text{f}$, what frequency will they resonate at?

5. ANSWERS TO PROBLEMS

Series Problems

1. $X_L = 37.7 \text{ ohms}$, $X_C = 66.3 \text{ ohms}$, $Z = 57.5 \text{ ohms}$, $I = 3.48 \text{ a}$, $E_{XL} = 131 \text{ volts}$, $E_{XC} = 230 \text{ volts}$, $E_R = 174 \text{ volts}$, phase angle $= 29.7^\circ$, cosine $\theta = 0.869$, $P_{app} = 696 \text{ VA}$, $P_t = 606 \text{ w}$.
2. $X_L = 314 \text{ ohms}$, $X_C = 398 \text{ ohms}$, $Z = 84.4 \text{ ohms}$, $I = 0.118 \text{ a}$, $E_{XL} = 37.2 \text{ volts}$, $E_{XC} = 47.0 \text{ volts}$, $E_R = 1.18 \text{ volts}$, phase angle $= 83.2^\circ$, cosine $\theta = 0.118$, $P_{app} = 1.18 \text{ VA}$, $P_t = 0.140 \text{ w}$.

Parallel Problems

1. $X_L = 3,014 \text{ ohms}$, $X_C = 2,652 \text{ ohms}$, $I_{XL} = 166 \text{ ma}$, $I_{XC} = 189 \text{ ma}$, $I_R = 25 \text{ ma}$, $I_{line} = 33.6 \text{ ma}$, and $Z = 14,900 \text{ ohms}$.
2. $X_L = 6,280 \text{ ohms}$, $X_C = 3,980 \text{ ohms}$, $I_{XL} = 0.795 \text{ ma}$, $I_{XC} = 1.26 \text{ ma}$, $I_R = 3.33 \text{ ma}$, $I_{line} = 3.36 \text{ ma}$, and $Z = 1,490 \text{ ohms}$.

Resonant Frequency Problems

1. 1,000 cps (approx)
2. 1,000 kc (approx)
3. 112 μf (approx)
4. 390 μf (approx)
5. 22 mc (approx)
6. 2.9 mc (approx)